The self-calibration method of geometric parameters for non-contact five-coordinate measuring machine

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KEYWORDS : Five-coordinate measuring machine, Measurement model, Parameter self-calibration, Laser measurement

Abstract: For some kind of tiny and easy-deformed objects with complex shapes, the dimensions of each geometric element and their mutual spatial location relationship are both need to be detected. Based on the practical measurement requirement, a specialized non-contact five-coordinate measuring machine is designed and built, in which the laser probe can inspect the object from arbitrary directions extensively. According to the structure form of this machine, its system measurement model is established. In the meantime, by analyzing the model, its nonrestraint optimization objective function is derived. In order to calibrate these unknown system geometric parameters, an improved genetic algorithm for this model is introduced subsequently. This method stated above is able to calibrate out the system geometric parameters easily and quickly. Especially when the laser probe is installed and fixed again, this method will exhibit its prominent convenience. Finally, the experiments illustrate the feasibility and robustness of this calibration approach.

Manuscript received: February 28, 2011 / Accepted: January XX, 2011

NOMENCLATURE

a = directional orientation of the system
h = strip thickness with strip thickness and strip thickness
strip thickness

1. Introduction

In recent decades, coordinate measuring machine(CMM) has achieved rapid development. Currently, CMM has been widely used in machining, automotive industry, electronics industry, aerospace industry and defense industry. Due to its own some limitations, the traditional contact CMM fails to test those soft, easy-deformed objects. Therefore, CMM is advancing towards the directions of intelligence, non-contact, non-orthogonal, high-precision[1].

As the modeling premise of CMM, the accurate identification and calibration of system parameters play a significant role. Literature [2] proposed a method to calibrate and adjust the installation location of laser probe with the position sensitive detector(PSD). The spatial location of laser probe can be obtained by the output voltage of PSD. However, this approach fails to isolate the eccentricity and inclination of laser probe effectively and accurately. Literature [3] introduced the installation error model of laser probe fixed on the rotator PH10. Nevertheless, the solving precision of this model depends on the rotating accuracy of PH10 directly.

The problem of solving the unknown geometric parameters can be transformed into solving the nonlinear optimization problem with multiple unknown variables. Imitating the theory of survival of the fittest in the nature, genetic algorithm does well in achieving the optimal solution by the operations of selection, crossover and mutation. Comparing with other optimization methods, genetic algorithm is an effective approach with its outstanding advantages[4-6]. Aiming at the deficiency that it is prone to be premature, an improved genetic algorithm is introduced in this paper. By computing the Euclidean distance between the individuals, those similar individuals are eliminated from the population. Hence, the diversity of the population comes true and effectively avoids the occurrence of premature phenomenon.

2. Establishment and calibration of System measurement model

2.1 Mechanical structure of this machine

By comparison, the mechanical structure form of base and cantilever beam is selected presented in Fig.1. The laser displacement sensor is located at the front of cantilever beam and can rotate around A and B axes while moving along Z axis. The tested object lies on the worktable which can travel along X axis and Y axis in horizontal direction. The step motors with subdivision function are applied to drive each axis. Among them, the motor for A axis has contracting brake device which will lock the motor mainshaft and prevent collision of the probe and worktable in case of accidental power off. The high-precision ball screws are used to drive X and Y axes. Considering the layout rationality of motor, the transmission of Z axis adopts the hybrid form of synchronous belt and ball screws. The motor for A axis drives the probing system with planetary gear reducer directly. The motor for B axis drives the laser probe through planetary gear reducer and synchronous belt. Meanwhile, in order to balance the gravity effect of beam components, a sixteen kilogram counterweight is hanging behind the column. The materials of the base and column are both natural marble because of its outstanding stability.

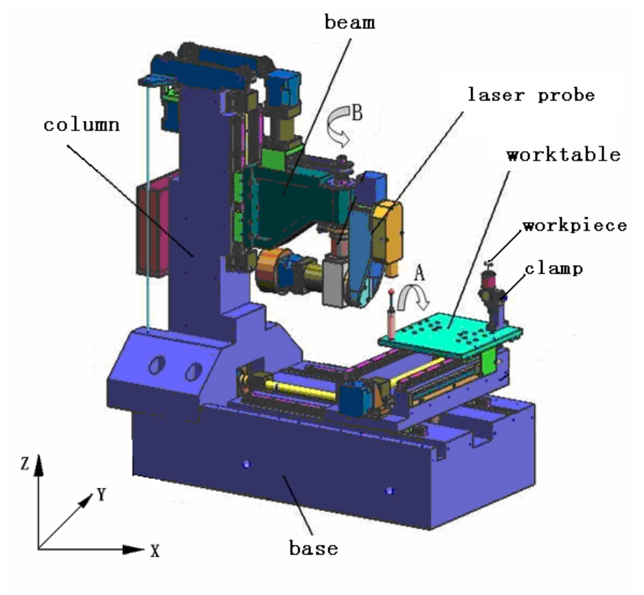

Fig.1 The mechanical structure of the five-coordinate Measuring machine

The prominent advantage of such structure lies in the fact that the object can be detected from different directions as extensively as possible. Compared to the existing three-coordinate measuring machine, no doubt, this five-coordinate measuring machine increases measurement flexibility. It is easier to acquire more detail information of objects. Also, because of its non-contact measurement, there is no worry to damage the tested objects. The strokes of A and B axes are $\pm 120^{\circ}$ and $\pm 90^{\circ}$ respectively. The ones of XYZ axes are $200mm \times 160mm \times 60mm$. As an example of measuring sphere surface, this machine is able to scan two thirds of the sphere surface by means of five axes linkage motion. Shown in Fig.2, the rest surface can be inspected easily except for the red shade area. To some extent, increase the height of the clamp, the measurable area will be larger.

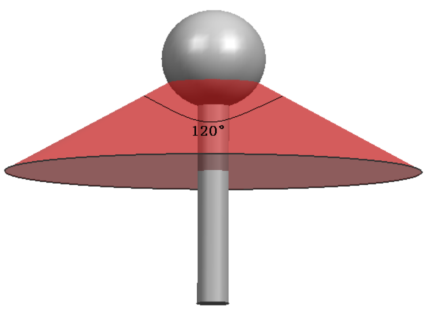

Fig.2 The measurable area and unmeasurable area

2.2 Establishment of system measurement model

First of all, at the beginning of measurement, the establishment of system measurement model is necessary.

Based on the structure form of this machine, four coordinate systems are introduced in Fig.3.

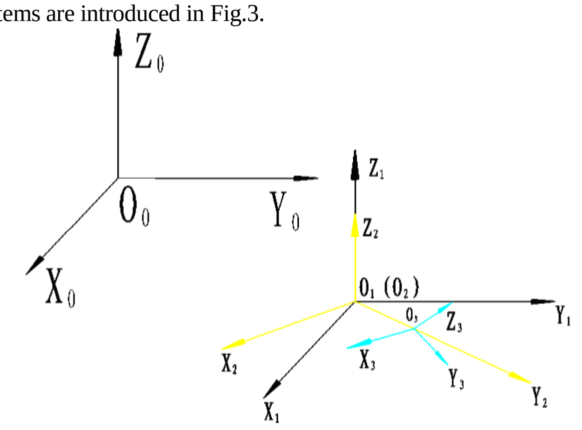

Fig.3 The relationship of four coordinate systems

(1) The machine coordinate system $O_0X_0Y_0Z_0$.

(2) The machine moving coordinate system $O_1X_1Y_1Z_1$. Its origin O_1 is the intersection point of the centreline of B axis and the horizontal plane containing the centreline of A axis. It doesn't change with the movement of each axis. The directions of its three axes are same with the ones of machine coordinate system.

(3) The coordinate system $O_2X_2Y_2Z_2$ based on B axis. Its origin is same with O_1. Its Z_2 axis is parallel to the Z axis of machine coordinate system. Its axis X_2 is parallel to the centreline of A axis. The direction of axis Y_2 is derived by right-hand rule.

(4) The coordinate system $O_3X_3Y_3Z_3$ based on A axis. The direction of axis X_3 is same with axis X_2. The direction of axis Z_3 is the one of axis Z which has rotated around A axis at a given angle. Its origin O_3 is the intersection point of X_3 and Z_3. The direction of axis Y_3 is derived by right-hand rule.

Analyzing the relationship among these four coordinate systems, There is a translation relationship between coordinate $O_1X_1Y_1Z_1$ and $O_0X_0Y_0Z_0$. The translation matrix is T_{10}.

$$T_{10} = Q_{10} \tag{1}$$

Where $Q_{10} = [x_{10}, y_{10}, z_{10}]^T$,which are the grating readings of XYZ axes.

There is an only rotation matrix around Z axis between $O_2X_2Y_2Z_2$ and $O_1X_1Y_1Z_1$.

$$T_{21} = R_{21} \tag{2}$$

Here, $R_{21} = \begin{bmatrix} \cos(\theta_B + \Delta\theta_B) & -\sin(\theta_B + \Delta\theta_B) & 0 \\ \sin(\theta_B + \Delta\theta_B) & \cos(\theta_B + \Delta\theta_B) & 0 \\ 0 & 0 & 1 \end{bmatrix}$,

θ_B is the rotation angle of B axis relative to measurement zero position. $\Delta\theta_B$ is a deviated angle of the centreline of A axis motor relative to measurement zero position, which is a very small given value usually.

There is a translation and rotation relationship between

$O_3X_3Y_3Z_3$ and $O_2X_2Y_2Z_2$.

$$T_{32} = R_{32} + Q_{32} \tag{3}$$

Here, $R_{32} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_A & -\sin\theta_A \\ 0 & \sin\theta_A & \cos\theta_A \end{bmatrix}$, $Q_{32} = [0, \Delta y_{32}, 0]^T$.

Δy_{32} is a translation value between the origins O_3 and O_2.

In the coordinate system $O_3X_3Y_3Z_3$, the optical axis equation of the laser probe is determinate. By assuming that $q(x, y, z)$ is the measured point, (x_{43}, y_{43}, z_{43}) are the coordinates of zero position of laser probe, the orientation vector of the optical axis is (l, m, n). If the reading of laser probe is t, the line equation of optical axis will be presented below.

$$\frac{x - x_{43}}{l} = \frac{y - y_{43}}{m} = \frac{z - z_{43}}{n} = t \tag{4}$$

Thus, the coordinates of q are written as follow in the $O_3X_3Y_3Z_3$.

$$\begin{bmatrix} x_q \\ y_q \\ z_q \end{bmatrix} = \begin{bmatrix} tl + x_{43} \\ tm + y_{43} \\ tn + z_{43} \end{bmatrix} = t\cdot R_{43} + Q_{43} \tag{5}$$

Here, $R_{43} = [l \quad m \quad n]^T$, $Q_{43} = [x_{43} \; y_{43} \; z_{43}]^T$.

By means of coordinate transformation relationship, the reading of laser probe can be transformed into the machine coordinate system $O_0X_0Y_0Z_0$. Suppose the current reading of laser probe is t, its corresponding coordinates are $(x_{q0}, y_{q0}, z_{q0})^T$ in the machine coordinate system. Substitute equation (1)-(5) into equation (6).

$$\begin{bmatrix} x_{q0} \\ y_{q0} \\ z_{q0} \end{bmatrix} = T_{10}\cdot T_{21}\cdot T_{32}\cdot \begin{bmatrix} x_q \\ y_q \\ z_q \end{bmatrix} \tag{6}$$

Equation (7) can be obtained after the simplification of equation (6).

$$\begin{bmatrix} x_{q0} \\ y_{q0} \\ z_{q0} \end{bmatrix} = R_{21}\cdot(R_{32} + Q_{32})\cdot(t\cdot R_{43} + Q_{43}) + Q_{10} \tag{7}$$

Equation (7) is right the measurement model of this machine.

2.3 Calibration of system measurement model

In equation (7), the solution of unknown parameters can get help from measuring a given spatial point, such as the center of a standard ball. Obviously, when the laser probe reaches a specific location, the angle θ_A and θ_B is known and unchanged. Then the value of $R_{21}\cdot(R_{32} + Q_{32})\cdot(t\cdot R_{43} + Q_{43})$ is denoted as $(\Delta x, \Delta y, \Delta z)^T$.

$$\begin{bmatrix} x_{q0} \\ y_{q0} \\ z_{q0} \end{bmatrix} = \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} + \begin{bmatrix} x_{10} \\ y_{10} \\ z_{10} \end{bmatrix} \tag{8}$$

From equation (8), when the laser probe is in a given posture, scan a standard ball with the laser probe and obtain its centre S_1.

$$S_0 = S_1 + (\Delta x, \Delta y, \Delta z)^T \tag{9}$$

Here, $S_0(x_0, y_0, z_0)$ denote the ball center coordinates in the machine coordinate system. So, if the laser probe scans the standard ball once in one posture, three equations will be established. Consequently, the measurement data in four postures is enough to solve eight unknown parameters in the measurement model and three ball center coordinates (x_0, y_0, z_0). In addition, because R_{43} is a unit vector, a constraint equation is added. Construct the objective function as follows.

$$\begin{cases} F(X) = \sum_{i=1}^{n} \left\| S_0^{(i)} - S_0 \right\|^2 = \min \\ h = l^2 + m^2 + n^2 - 1 = 0 \end{cases} \tag{10}$$

Transform the constraint optimization function into the nonrestraint optimization function by means of the penalty function.

$$G(X) = \sum_{i=1}^{n} \left\| S_0^{(i)} - S_0 \right\|^2 + M\cdot h^2 \tag{11}$$

where, n is the measurement times. M says the penalty factor.

2.4 Improved genetic algorithm

In order to identify and calibrate the unknown system parameters, an improved genetic algorithm is adopted in this work.

(1) Coding. Here real number coding is applied to prevent the occurrence of "Hamming cliff".

(2) Generate the initial population with N samples at random.

(3) Design the fitness evaluation function as follows.

$$Fit(X) = \frac{1}{1 + G(X)} \tag{12}$$

From the definition of objective optimization function, it is clear that $Fit(X) \geq 0$. According to equation (12), calculate the fitness value of each individual. To avoid the premature, the traditional genetic algorithm is improved as below.

(3.1) In light of the fitness value of each individual, resort all individuals in descending order.

(3.2) Calculate the fitness mean value of all of individuals, reserve those individuals in which their fitness value is greater than the mean value.

(3.3) Calculate the Euclidean distance between the reserved individuals. By assuming that the arbitrary two individual are $X_i = (x_{1i}, x_{2i} \cdots x_{11i})$ and $X_j = (x_{1j}, x_{2j} \cdots x_{11j})$, we have their Euclidean distance as following.

$$d_{ij} = \sqrt{(x_{1i} - x_{1j})^2 + (x_{2i} - x_{2j})^2 + \cdots + (x_{11i} - x_{11j})^2}$$

Taken the individual with highest fitness value as the template, eliminate those individuals between which and the template the distance is less than a given value ε.

(3.4) Repeat step (3.3).

(3.5) If the scale of population is met, turn to step (4). Or else, turn to step (3.4).

(4) The selection operator adopts the elitist strategy. Besides, two-point crossover operator and Gaussian mutation operator are used for the population.

(5) Iteration termination judgment. If the value of $Fit(X)$ is less than 10^{-6} or the maximum of evolution generations reaches 1000, terminate the iteration.

4. Experiments

The designed and built five-coordinate measuring machine is present in Fig.7. The laser probe adopts CONO probe with HD25 lens coming from Israel. Its working parameters are listed in table 1. The CCD is Hitachi KP-F140 with 1392x1024 pixels.

Table 1 The working parameters of laser probe

type	resolution	repeatability	range	standoff
Cono+HD25	0.1um	0.2um	0.6mm	14mm

The parameters of genetic algorithm are set as: population size is 500, crossover probability is 0.5, mutation probability is 0.05, penalty factor $M = 10^4$. Under the four postures of laser probe, ball center coordinates are listed in table 2.

Table 2 The ball center coordinates

$t(mm)$	$(\theta_A, \theta_B)(\deg ree)$	$S_1(mm)$
0	(0, 0)	(0.001743,0.002189,-4.725415)
0.2	(90, 0)	(0.088509,-30.046754 ,4.432010)
0.4	(-90, 0)	(-0.012881, 9.609871, 25.132104)
0.6	(90, 90)	(-139.878714,-130.717940,4.430974)

Fig.4 exhibits the solving results of traditional genetic algorithm and improved genetic algorithm clearly. It can be seen that the convergence speed of improved genetic algorithm is obviously faster than the traditional genetic algorithm. The values of eleven system parameters are presented below.

$$\Delta\theta_B = -0.722465,\quad \Delta y_{32} = 0.782104$$

$$\begin{bmatrix} l \\ m \\ n \end{bmatrix} = \begin{bmatrix} 0.109543 \\ 0.047720 \\ 0.976634 \end{bmatrix}$$

$$(x_{43}, y_{43}, z_{43}) = (119.982704, 9.864540, 20.204917)$$

$$(x_0, y_0, z_0) = (-119.961064, -9.877542, 15.479502)$$

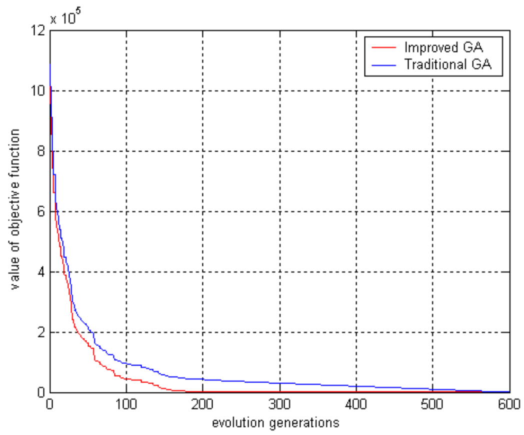

Fig.4 The comparison of two kinds of genetic algorithm

By means of improved genetic algorithm, repeated solving results show the solution precision can reach sub-micron level, which meets the precision requirement of calibration pretty well.

In order to examine the effect of this model, scan the $\Phi 12$ standard ball five times with static measuring mode under two conditions respectively. The measurement path refers to Fig.5. The pre and post measurement results are listed in table 3 by adopting model.

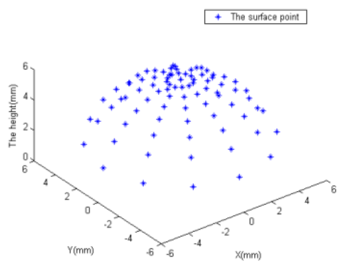

Fig.5 The measurement path

Table 3 Pre and post measurement results

No.	1	2	3	4	5
Pre calibration(mm)	6.0128	6.0122	6.0119	6.0114	6.0122
Post calibration(mm)	5.9997	6.0009	6.0006	5.9993	6.0003

From table 3, it can be seen that the measuring precision is enhanced $12\mu m$ or so. The measuring uncertainty of this machine deduces from $(11.82 + L/1000)\mu m$ to $(1.96 + L/1000)\mu m$.

5. Conclusions

(1) Based on the practical measurement demand, a non-contact five-coordinate measuring machine is designed and built.

(2) Its mechanical structure and function are introduced.

(3) Establish its system measurement model. Furthermore, an improved genetic algorithm is used to achieve the solution of this model.

(4) Experiments illustrate the validity and feasibility of the model.

(5) It is worth mentioning that such measurement model is suitable for scanning probe, as well as trigger-touch probe.

ACKNOWLEDGEMENT

The authors wish to express gratitude to China Academy of Engineering Physics, which has supported this work.

REFERENCES

1. Zhang Guoxiong. Development orientations of coordinate measuring techniques. Infrared and Laser Engineering, Vol. 37, No. 4, pp.2-5, 2008.
2. Fang Jiawei, Zhang Guoxiong, Qiu Zurong. Calibration system for surveying axis of non-contact laser probe. Electronic Measurement Technology, Vol. 29, No. 3, pp. 160-161, 2006.
3. Song Kaichen. A Research on the System of CMM's Laser Scanning Measurement. Tianjin University, 1997.
4. Wang Xiaoping, Cao Liming. The theory, application and software implementation of genetic algorithm. Xi'an Jiaotong University press, 1998.
5. Wen Xiulan, Song Aiguo. An improved genetic algorithm for planar and spatial straightness error evaluation. International Journal of Machine Tools and Manufacture, Vol. 43, No. 11, pp. 1157-1162, 2003.
6. Lai H Y, JYWE W Y, Chen C K, et al. Precision modelingof form errors for cylindricity evaluation using genetic algorithm. Precision Engineering, Vol. 24, No. 4, pp. 310-319, 2000.
7. Han Ruifeng, Zhang Yongkui. An Improved Genetic Algorithm Coded with Real Number. Computer Engineering and Application, Vol. 38, No. 13, pp. 78-80, 2002.
8. Wang Chengdong, Zhang Youyun. Adaptive Pseudo-Parallel Genetic Algorithm Based on Real Coding . Journal of Xi'anJiaotong University, Vol. 37, No. 7, pp. 707-710, 2003.